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Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review

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[1] The increasing and alarming trend of degradation and deforestation of tropical peat swamp forests may contribute greatly to climate change. Estimates of carbon (C) losses associated with land use change in tropical peatlands are needed. To assess these losses we examined C stocks and peat C fluxes in virgin peat swamp forests and tropical peatlands affected by six common types of land use. Phytomass C loss from the conversion of virgin peat swamp forest to logged forest, fire-damaged forest, mixed croplands and shrublands, rice field, oil palm plantation, and *Acacia* plantation were calculated using the stock difference method and estimated at 116.9 ± 39.8, 151.6 ± 36.0, 204.1 ± 28.6, 214.9 ± 28.4, 188.1 ± 29.8, and 191.7 ± 28.5 Mg C ha^{-1}, respectively. Total C loss from uncontrolled fires ranged from 289.5 ± 68.1 Mg C ha^{-1} in rice fields to 436.2 ± 77.0 Mg C ha^{-1} in virgin peat swamp forest. We assessed the effects of land use change on C stocks in the peat by looking at how the change in vegetation cover altered the main C inputs (litterfall and root mortality) and outputs (heterotrophic respiration, CH_4 flux, fires, and soluble and physical removal) before and after conversion. The difference between the soil input-output balances in the virgin peat swamp forest and in the oil palm plantation gave an estimate of peat C loss of 10.8 ± 3.5 Mg C ha^{-1} yr^{-1}. Peat C loss from other land use conversions could not be assessed due to lack of data, principally on soil heterotrophic respiration rates. Over 25 years, the conversion of tropical virgin peat swamp forest into oil palm plantation represents a total C loss from both biomass and peat of 427.2 ± 90.7 Mg C ha^{-1} or 17.1 ± 3.6 Mg C ha^{-1} yr^{-1}. In all situations, peat C loss contributed more than 63% to total C loss, demonstrating the urgent need in terms of the atmospheric greenhouse gas burden to protect tropical virgin peat swamp forests from land use change and fires.

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1. Introduction

[2] Despite covering only about 0.25% of the Earth's land surface, tropical peatlands contain around 3% of the global soil carbon (C) stocks and at least 20% of global peat C [*Page et al.*, 2004; *Page and Banks*, 2007]. The largest area of tropical peatlands occurs in Southeast Asia, where they are found in Indonesia (predominantly Sumatra, Kalimantan and West Papua), Malaysia (Peninsular Malaysia, Sarawak and Sabah), Brunei and Thailand [*Rieley and Ahmad-Shah*, 1996]. The majority of these are lowland, ombrotrophic systems, in which water and nutrient supplies to the peat surface are derived entirely from precipitation [*Page et al.*, 2004].

[3] In their natural state, lowland tropical peatlands support a growth of swamp forest overlying peat deposits up to 20 m thick [*Page et al.*, 1999]. Peat formations in Indonesia, Malaysia and Brunei present a dome shape [*Jaenicke et al.*, 2008], which leads to a progression of forest types from the edge to the interior [*Laumonier*, 1996; *Page et al.*, 1999]. Virgin peat swamp forests in Indonesia have been classified into three major types, namely, (1) mixed peat swamp forests on shallow to moderate peat layers between 1.5 and 6 m depth, (2) pole forests (low or tall) on deep peat layers, and (3) tall interior forests where the peat is thickest [*Laumonier*, 1996; *Brady*, 1997; *Page et al.*, 1999]. Peat soils are characterized by high C contents over the full depth of the peat deposit and very low bulk densities (<0.2 g cm^3) [*Andriesse*, 1988]. Anaerobic conditions in the soil limit decomposition of the litter, leading to peat accumulation and also channel a small fraction of the excess organic matter (OM) into CH_4 [*Jauhiainen et al.*, 2005], which is a greenhouse gas (GHG) with a global warming potential 25 times stronger than CO_2 [*Forster et al.*, 2007] over a 100 year time horizon.

[4] Currently around 25% of all forest degradation and deforestation in Southeast Asia occurs on peatlands [*Hooijer*

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et al., 2006]. This deforestation is driven by wood production and demand for land on which to establish small- and large-scale agriculture including oil palm and timber plantations [*Hooijer et al.*, 2006]. Accessible peat swamp forests of Southeast Asia are often logged, legally or not. When the forest is logged, the biomass and soil organic carbon (SOC) stocks decrease through increased mineralization and incidence of fire [*Brady*, 1997; *Page et al.*, 2002; *Langner et al.*, 2007; *Langner and Siegert*, 2009]. Biomass C stocks of logged forests in Indonesia were estimated to be around 50%–60% of nearby natural forests [*Palm et al.*, 2000; *Boehm et al.* 2001]. In addition, cutting canals in order to extract the logged wood is a widespread practice in Southeast Asia that results in a subsidence of the peat dome [*Kool et al.*, 2006], a fall of the water tables and consequently induces increased OM oxidation rates [*Hooijer et al.*, 2006]. When peatlands are reclaimed for other uses, the forest is cleared and the land is prepared for cultivation, often using fire. Some of these fires spread out of control, consuming not only the surface vegetation but also the underlying peat and tree roots [*Page et al.*, 2002]. Drainage ditches are often constructed to lower the groundwater level and the soil may be compacted with heavy machinery to allow anchorage of trees and to increase the bearing capacity of the soil [*Andriesse*, 1988; *Wösten et al.*, 1997]. Increased aeration due to drainage may also result in decreased CH_4 production and increased CH_4 consumption by peat soils [*Melling et al.*, 2005a]. Large areas of tropical peatlands will continue to be cleared to establish oil palm and *Acacia* plantations [*Barr*, 2001; *Miettinen*, 2004; *Hooijer et al.*, 2006; *Germer and Sauerborn*, 2008] and to a lesser extent, sago palm and rubber.

[5] Our aim was to evaluate C losses associated with land use change (LUC) in tropical peat swamps of Southeast Asia. C losses may be assessed either from changes in C stock (stock difference method) or changes in C flows (input-output method). The first method requires estimates of C stocks in a given pool prior to and following conversion [*IPCC*, 2006]. The second method requires estimation of the annual rates of C gains and losses in a pool [*IPCC*, 2006], prior to and following conversion. As a first step, we reviewed studies of C stocks in the five C pools recommended by IPCC (aboveground and belowground biomass, dead wood, litter, and soil organic matter) of seven land use (LU) types prevalent in Southeast Asia: virgin peat swamp forest, logged forest, fire-damaged forest, mixed croplands and shrublands, rice fields, oil palm and *Acacia* plantations. From this compilation we quantified C stock changes in the phytomass resulting from virgin peat swamp forest conversion to the other LUs using the stock difference approach. With the same method, we assessed C stock changes in both phytomass and peat resulting from uncontrolled fires, using average peat C stock loss from fires.

[6] An accurate assessment of soil C stock changes following LUC in tropical peatlands requires C stocks measurements over the full depth of the peat profile. Such studies were not available in the literature therefore our approach to estimate peat C stocks losses is based on reviewing C fluxes into and out of the peat in the LU categories and using IPCC equations to calculate emissions. Using the data available in the scientific literature for land use systems on peat from Southeast Asia, we combined the results with C stock losses from the aboveground biomass to develop estimates of total C loss from vegetation and peat for the conversion of virgin peat swamp forest to oil palm plantation on peat. Due to lack of suitable data, a similar assessment could not be calculated for the other types of LUCs. From this we identified major gaps in knowledge and priorities for data collection to better constrain these estimates.

2. Materials and Methods

2.1. Data Collection, Calculation, and Presentation

[7] We collected data from a variety of published sources including journal articles, theses and reports. When the C content of dry matter in the phytomass was not provided in a publication, we used a value of 50% [*IPCC*, 2003]. For rice fields, mixed croplands and shrublands, oil palm and *Acacia* plantations, we assumed that vegetation grows similarly on a peat soil as it does on a mineral soil since almost no biomass values and/or C fluxes were available for these LUs on peat soils.

2.1.1. C Stocks and Stock Changes

[8] We considered litter and dead wood as one pool (necromass) because most reports do not make a distinction between the two pools. Table 1 presents the methods, the reference of the data sources and C stock values in the aboveground biomass, necromass and belowground biomass. Total phytomass C stocks were calculated as the sum of the average C stocks in the different pools.

[9] Original data used for C stocks calculation within the different pools in virgin peat swamp forests is available in Table S1.[1] In the category mixed croplands and shrublands, we included annual crops (cassava, soybean, etc.), shrublands and also fruit agroforestry systems and homegardens. In oil palm and *Acacia* plantations, we used the time-averaged C stock which is defined as the integral over time of the C stocks in each phase of the system cycle, divided by the duration of this cycle [*Palm et al.*, 2000]. The time-averaged C stock in *Acacia* plantations was calculated on the basis of a 6 year rotation, which is common in many parts of the region [*Verchot et al.*, 2010]. We developed relationships between the age of *A. mangium* plantations and C stocks in the aboveground tree biomass and C stocks in root biomass; over the first 11 years of stand growth. A Gompertz growth model [*Yoshimoto*, 2001] (based on 40 measurement points) was developed for the aboveground trees biomass whereas a linear model (using 14 points) was developed for the root biomass. Integrating these models and dividing by 6 gave the time-averaged aboveground and belowground biomass C stock in *Acacia* plantations.

[10] Mean surface (above 20 cm depth) peat C density in virgin peat swamp forests was calculated using 13 paired bulk density and C content values [*Brady*, 1997; *Page et al.*, 2004; *Melling et al.*, 2005b].

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[1] Auxiliary materials are available with the HTML. doi:10.1029/2009GB003718.

Table 1. Method, Data Sources, and C Stock Value in the Aboveground Biomass, Necromass, and Belowground Biomass of Different Land Use Treatments[a]

Land Use	Aboveground Biomass			Necromass			Belowground Biomass		
	Method[b]	Sources[c]	Value[d]	Method[b]	Sources[c]	Value[d]	Method[b]	Sources[c]	Value[d]
F	Average (a)	1, 2, 3, 4	181.9 ± 25.6 (14)	Average (a)	1, 3	13.0 ± 3.4 (6)	Average (a)	1	24.8 ± 12 (5)
LF	Proportion of F(b)	3, 4	85.1 ± 23.5 (17) (=47 ± 11% (3) × F)	Proportion of F (b)	3, 4	6.1 ± 2.2 (9) (=47 ± 11% (3) × F)	Proportion of F (b)	3, 4	11.6 ± 6.3 (8) (=47 ± 11% (3) × F)
FF	Proportion of F(b)	5, 3, 6	56.4 ± 17.4 (19) (=31 ± 8% (5) × F)	Proportion of F (b)	5, 3, 6	4.0 ± 1.5 (11) (=31 ± 8% (5) × F)	Proportion of F (b)	5, 3, 6	7.7 ± 4.3 (10) (=31 ± 8% (5) × F)
C&S	Average (a)	7, 8, 9, 10, 11, 12, 13, 14	12.4 ± 2.4 (44)*	Average (a)	7, 8, 9, 10, 11, 12, 13, 14	-	Average (a)	8, 15, 14	3.3 ± 1.3 (11)
R	Average (a)	16, 17, 18	4.8 ± 0.3 (6)**	Average (a)	16, 17, 18	-	Average (a)	16, 17, 18	-
OP	Review (c)	19	24.2 ± 8.1 (51)	Review (c)	19	1.2 ± 0.5	R:S ratio (d)	20	6.2 ± 3.5 (51)
A	Growth model (e)	21, 22, 23, 24, 25, 15, 26, 27, 28, 29, 30	20.9 ± 2.1 (40)	Average (a)	31, 23, 32, 15, 33	3.8 ± 0.7 (12)	Growth model (e)	22, 34, 15, 28	3.3 ± 0.1 (14)

[a] F, virgin peat swamp forest; LF, logged forest; FF, fire-damaged forest; C&S, mixed croplands and shrublands; R, rice field; OP, oil palm plantation; A, *Acacia* plantation.

[b] Method: (a), Average value calculated from data available in literature; (b), Calculated as a proportion of biomass compared to reference virgin peat swamp forests; (c), Data from literature review; (d), Relationship between root biomass and shoot biomass; (e), Integration of statistical growth model based on data in literature (Gompertz exponential model (Figure 1a) and linear model (Figure 1b) for the aboveground and belowground C stocks, respectively) divided by a rotation time of 6 years.

[c] Sources: 1, *Brady* [1997]; 2, *Waldes and Page* [2001]; 3, *Ludang and Palangka Jaya* [2007]; 4, *Verwer and van der Meer* [2010]; 5, *Page et al.* [2002]; 6, *Rieley and Page* [2008]; 7, *Halenda* [1989]; 8, *Jensen* [1993]; 9, *Hashimotio et al.* [2000]; 10, *Hartemink* [2001]; 11, *Palm et al.* [2000]; 12, *Swamy and Puri* [2005]; 13, *Jepsen* [2006]; 14, *Johnson et al.* [2006]; 15, *Syahrinudin* [2005]; 16, *Matthews et al.* [2000]; 17, *Pathak et al.* [2005]; 18, *Huang et al.* [2009]; 19, *Germer and Sauerborn* [2008]; 20, *Henson and Dolmat* [2003]; 21, *Awang and Taylor* [1993]; 22, *Bernhard-Reversat et al.* [1993]; 23, *Ihwanudin* [1994]; 24, *Pudjiharta* [1995]; 25, *Hiratsuka et al.* [2004]; 26, *Wachrinrat et al.* [2005]; 27, *Thanyapraneedkul and Susaki* [2006]; 28, *Heriansyah et al.* [2007]; 29, *Torres Vélez and Del Valle* [2007]; 30, *Laclau et al.* [2008]; 31, *Tsai* [1988]; 32, *Wibowo* [1996]; 33, *Nuruddin and Pangalin* [2007]; 34, *Högberg and Wester* [1998].

[d] Value: Values are mean ± standard error (*n*), expressed in Mg C ha^{-1}; *, includes both aboveground biomass and necromass; **, includes aboveground biomass, necromass, and belowground biomass.

[11] Finally, total C loss from uncontrolled fires was calculated as the sum of the average fire related peat C stock loss (average value calculated from Table S2) and phytomass C stock loss. In virgin and logged peat swamp forest, phytomass C loss from the fire was calculated as the difference between total C stock in these treatments and that in the fire-damaged forest. In mixed croplands and shrublands, rice fields, oil palm and *Acacia* plantations, we estimated phytomass C loss from the fire to be equivalent to total phytomass C stocks, assuming that most of the phytomass was burnt and that the rest was left to decompose.

2.1.2. Soil C Fluxes and Flux Changes

[12] The IPCC default method for estimating emissions from soils based on changes in stocks over time [*IPCC*, 2006] is difficult to implement accurately in tropical peatlands. Instead, we assessed the changes in soil C inputs and outputs. We calculated C inputs to the soil from litterfall and root mortality. The main soil C outputs are: mineralization (also called heterotrophic respiration), methanogenesis, leaching, runoff, erosion and fires. Table 2 presents the methods and the reference of the data sources used for calculating litterfall, root mortality, heterotrophic soil respiration and land-clearing fire outputs. In all LU treatments total C inputs to the peat were calculated as the sum of the average C inputs from litterfall and root mortality.

[13] In virgin peat swamp forests, annual root mortality was assumed to equal annual root production, which is a reasonable assumption for understanding short-term soil C dynamics [*Hertel et al.*, 2009].The average C input from fine root production was calculated using the values presented in Table S3. Table S3 also includes the litterfall rates and proportion of root inputs to total inputs to the peat for the corresponding studies.

[14] Because there are no published litterfall and root mortality rates in logged and fire-damaged peat swamp forests, we used relationships obtained from measurements in mineral soils. From the results of *Hertel et al.* [2009], we established relationships between the remaining biomass in the forest after disturbance and C inputs from (1) litterfall and (2) root mortality in logged and fire-damaged forests, expressed as a percentage of C inputs from litterfall and root mortality, respectively, in the virgin peat swamp forest. We applied to these relationships the percentage of remaining phytomass after logging and fire from Table 1.

[15] Mean soil respiration rates, CH_4 fluxes and associated water table depths were calculated for the different LU treatments (original data available in Tables S4 and S5). We also explored correlations between soil CO_2 and CH_4 fluxes and two important abiotic factors, soil temperature and water table level, by LU treatment. Given the high variation in the responses of soil CO_2 and CH_4 fluxes to LUC among sites, we used a meta-analysis statistical approach to compare soil respiration and CH_4 fluxes before and after LUC. We used data from studies with paired observations on the same site. Seven bibliographic references (Table S4) were included in the meta-analysis of soil respiration, representing 19 case studies of conversion from a virgin peat swamp forest to another land use. Six bibliographic references (Table S5) were included in the meta-analysis of CH_4 fluxes, considering 16 case studies of conversion from a

Table 2. Method and Data Sources for Calculation of C Fluxes Into and Out of the Soil for Different Land Use Treatments[a]

	Soil C Inputs				Soil C Outputs			
	Litterfall		Root Mortality		Heterotrophic Respiration		Land-Clearing fires	
Land Use	Method[b]	Sources[c]	Method[b]	Sources[c]	Method[b]	Sources[c]	Method[b]	Sources[c]
F	Average (a) corrected in order to include large-branch fall	1, 2, 3, 4, 5, 6 corrected using 4	Average (a)	1, 7, 5	Proportion of total soil respiration (b)	8		
LF, FF	Proportion C inputs in F (c)	9	Proportion C inputs in F (d)	9				
C&S	Average (a)	10, 7	Average (a)	10, 11				
R	Average (a)	12, 13	Average (a)	12, 13				
OP	Review (e)	14	Average (a)	15, 14	(Total respiration–root respiration) (f)	15	(Depth of peat burnt × surface peat C density)/ rotation time (g)	16
A	Average (a)	17, 18, 19, 20, 21, 22	Estimate (h)	22			Same as for OP	

[a]F, virgin peat swamp forest; LF, logged forest; FF, fire-damaged forest; mixed C&S, croplands and shrublands; R, rice field; OP, oil palm plantation; A, *Acacia* plantation. For total soil respiration and CH_4 fluxes, see Tables S4–S5.

[b]Method: (a) Average value calculated from data available in literature, (b) Proportion of total soil respiration that can be allocated to heterotrophic respiration, applied to mean total soil respiration assessed in this study (Table 5), (c) Proportion of C inputs from litterfall in the virgin peat swamp forest (Figure 2), (d) Proportion of C inputs from root mortality in the virgin peat swamp forest (Figure 2), (e) Data from literature review, (f) Difference between total respiration assessed in this study (Table 5) and mean root respiration from data available in the literature, (g) Depth of peat burnt estimated in the literature multiplied by the surface peat C density assessed in this study and divided by the rotation time of the plantation, (h) Estimate found in the literature.

[c]Sources: 1, *Brady* [1997]; 2, *Rahajoe et al.* [2000]; 3, S*ulistiyanto* [2004]; 4, *Chimner and Ewel* [2005]; 5, *Shimamura and Momose* [2005]; 6, *Harrison et al.* [2007]; 7, *Chimner and Ewel* [2004]; 8, *Ishida et al.* [2001]; 9, *Hertel et al.* [2009]; 10, *Hairiah et al.* [2000]; 11, database of *Gill and Jackson* [2000]; 12, *Hairiah et al.* [1999]; 13, *Matthews et al.* [2000]; 14, *Lamade and Bouillet* [2005]; 15, *Henson and Dolmat* [2003]; 16, *Rieley and Page* [2008]; 17, *Tsai* [1988]; 18, *Bernhard-Reversat et al.* [1993]; 19, *Ihwanudin* [1994]; 20, *Pudjiharta* [1995]; 21, *Mindawati* [2000]; 22, *Laclau et al.* [2008].

virgin peat swamp forest to another LU. In the meta-analysis, the control treatment was the virgin peat swamp forest and the "other land use" treatment included all other land uses than virgin peat swamp forest.

[16] Soluble and physical C loss included dissolved organic carbon (DOC) and particulate organic carbon (POC). DOC export from temperate and boreal peatlands ranges between 10 and 500 kg DOC ha^{-1} y^{-1}, which represents about 10% of the C released [*Holden*, 2005]. POC release from northern peatlands ranges from 20 to 400 kg ha^{-1} yr^{-1}, which is almost the same amount as DOC loss [*Holden*, 2005]. There are no such estimates in the tropics; however, some recent studies [*Yoshioka et al.*, 2002; *Yule and Gomez*, 2009] measured DOC concentrations in tropical virgin peat swamp forests (50–124 mg C L^{-1}) that were about twice those in northern peatlands (20–60 mg C L^{-1} [*Holden*, 2005]). DOC concentrations in the rivers draining tropical virgin peat swamp forests were also high (6–31 mg C L^{-1}) [*Yoshioka et al.*, 2002; *Baum et al.*, 2007]. Therefore, we assumed a loss from soluble and physical removal of 1 ± 0.5 Mg C ha^{-1} yr^{-1} for all LUs, using the combined maxima of what was observed in northern peatlands for POC and DOC.

2.1.3. Combination of the Stock and Flux Approaches for Assessing C Loss From Virgin Peat Swamp Forest Conversion

[17] C loss from virgin peat swamp forest conversion was assessed combining the stock and flux approaches. C loss from the peat was calculated as the difference between the balance of peat C inputs and outputs in the virgin peat swamp forest and that after conversion. C loss from vegetation cover change included loss from aboveground C stocks in trees only, since C flux from litter and roots was already taken into account in the soil input-output method. An assessment of C loss combining the stock and flux approaches could be achieved only for the conversion of virgin peat swamp forest to oil palm plantation due to lack of data on peat C fluxes in other LU treatments.

2.2. Statistics Analysis

[18] Statistical analysis was performed using the software *InfoStat* [2004], with a probability level of 0.05 to test the significance of the treatments effects. The *t* test and the nonparametric Mann-Whitney test were used to compare two means for normally and nonnormally distributed variables, respectively. For multiple comparisons, ANOVA and the nonparametric Kruskal Wallis test were performed, respectively, on normally and nonnormally distributed variables.

[19] Uncertainties estimates are reported as standard errors. In all calculations, the Gaussian error propagation (GEP) method was used for propagating uncertainties. This method is adequate for step-by-step calculations that are intended to compute ecological quantities that can be expressed as an analytical equation using addition, subtraction, multiplication and division, such as C stocks or fluxes [*Lo*, 2005]. The method assumes that uncertainties can be considered to be independent and normally distributed [*Malhi et al.*, 2009]. For addition and subtraction, uncertainties are propagated by quadrature of absolute errors, for multiplication and division propagation is by quadrature of relative error [*Malhi et al.*, 2009]. In the calculation of the average of *n* values, whenever the uncertainty of at least one value was missing, the average uncertainty was calculated as the standard error of

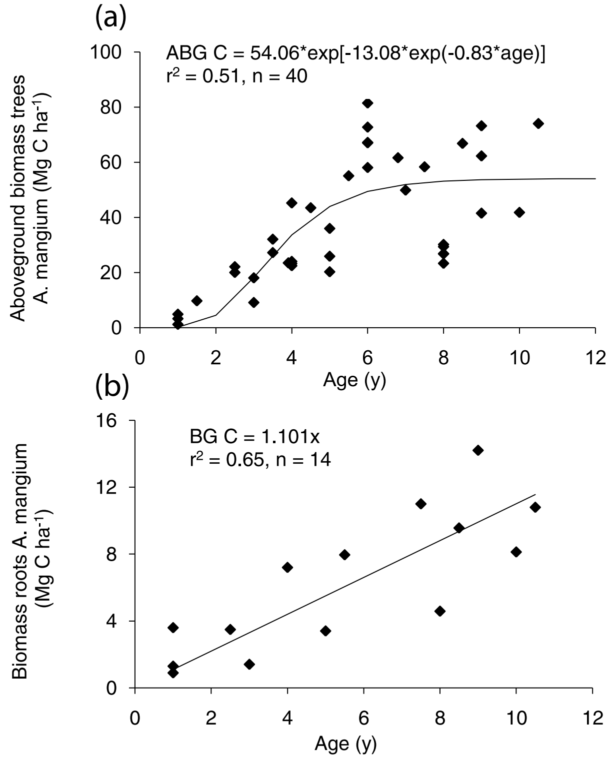

Figure 1. (a) Aboveground and (b) root biomass (Mg C ha^{-1}) of *Acacia mangium* trees as a function of the age of the plantation. The solid curve indicates the relationship based on measurements (solid diamonds) achieved by several authors (*Awang and Taylor* [1993], *Bernhard-Reversat et al.* [1993], *Ihwanudin* [1994], *Pudjiharta* [1995], *Hiratsuka et al.* [2004], *Syahrinudin* [2005], *Wachrinrat et al.* [2005], *Thanyapraneedkul and Susaki* [2006], *Heriansyah et al.* [2007], *Torres Vélez and Del Valle* [2007], and *Laclau et al.* [2008] for Figure 1a; and *Bernhard-Reversat et al.* [1993], *Högberg and Wester* [1998], *Syahrinudin* [2005], and *Heriansyah et al.* [2007] for Figure 1b. The equation of the relationships, the r^2 of the linear regression between observed and predicted trees aboveground C stocks (ABG C) (Figure 1a) and belowground C stocks (BG C) (Figure 1b), and the number of observations (n) are specified in the top left corner of each panel.

the n values. In such a case a comparison was made between the two uncertainties calculated: the standard error of the n values (SE_{Values}) and the standard error calculated using the GEP method (SE_{GEP}). In all cases, the largest error value was reported.

[20] Meta-analysis was used to evaluate the response of soil respiration and CH_4 fluxes to land use change (LUC) in tropical peatlands. Only the studies comparing a virgin peat swamp forest to another land use on the same site were included in the analysis (Tables S4–S5). The magnitude of the effect of LUC on soil respiration and CH_4 fluxes was evaluated using the Hedges' g metric (bias-corrected standardized mean difference) as defined by *Borenstein et al.* [2009]. Positive Hedges' g values indicated that LUC increased the value of the variable with respect to that in virgin peat swamp forest; negative values indicate that LUC decreased the value of the variable. According to *Borenstein et al.* [2009], Hedges' g values of 0.2 or less indicate a small effect size; values around 0.5 indicate a medium effect and 0.8 or above indicate a large effect size. The overall effect size was calculated using a random effects model which allows that the true effect could vary from study to study [*Borenstein et al.*, 2009], rather than using a fixed effect model for which the true effect size is assumed to be shared by all the included studies. A t test was used to assess the significance of individual and overall LUC effect sizes on the variables. The meta-analyses were performed with the software Comprehensive Meta Analysis version 2.2.048 (Biostat Incorporated, Englewood, New Jersey, United States).

3. Results

3.1. C Stocks and Stock Changes

[21] C distribution within pools varied greatly with the type of virgin peat swamp forest as did the ratio between fine roots and tree stems (Table S1). The relationships between the age of *A. mangium* plantations and C stocks in the aboveground tree biomass and in root biomass are presented in Figures 1a and 1b, respectively. C stocks in the aboveground biomass, necromass and belowground biomass of the seven LU types are presented in Table 1.

[22] From the estimates of phytomass C stocks (Table 3), greatest C loss from phytomass is associated with conversion of virgin peat swamp forests into rice fields and mixed croplands and shrublands; the least loss is associated with selective logging. Conversion to oil palm and *Acacia* plantations lead to intermediate C loss from phytomass. *Hooijer et al.* [2006] projected that in the coming years deforested and degraded lowland peatlands in Southeast Asia will be 11% recently cleared and burnt areas, 68% mixed croplands and shrublands areas and 21% large croplands areas with mainly oil palm and *Acacia* plantations. Using this projection, we estimate an average emission of 195.3 ± 20.2 Mg C from the phytomass to the atmosphere for each ha of lowland peat swamp forest altered. This assumes no C storage in harvested wood products and does not take into account phytomass C loss that may have resulted from prior logging activity since the extent of logging, especially illegal logging, within virgin peat swamp forest areas is impossible to assess. To counterbalance the lack of C loss from logging activity, our calculation considered that recently cleared and burnt areas corresponded to a conversion from virgin peat swamp forests to fire-damaged forests, which releases more C than when a logged forest is cleared, for instance.

[23] As a result of a high variability in peat bulk density and C content values, the C density varies greatly. We estimated a mean surface (above 20 cm depth) peat C density of 56.7 ± 6.5 kg C m^{-3} (n = 13) with minimum and maximum values of 37.9 and 106.5 kg C m^{-3}, respectively.

[24] Total C losses from peat and phytomass losses arising from uncontrolled fires are presented in Table 4 for virgin and logged peat swamp forests, mixed croplands and shrublands, rice fields, oil palm and *Acacia* plantations.

Table 3. Time-Average C Stocks in the Phytomass for Different Land Use Treatments and Phytomass C Losses Associated With Virgin Peat Swamp Forest Conversion[a]

Land Use	Rotation Time (years)	Time-Averaged C Storage (Mg C ha^{-1} Over Rotation Time)	C Loss From Forest Conversion (Mg C ha^{-1} Over Rotation Time)	C Loss From Forest Conversion (% C Stock in the Forest)
F	-	219.7 ± 28.4 (25)	-	-
LF	-	102.8 ± 27.8 (27)	116.9 ± 39.8 (27)	53.2 ± 19.4 (27)
FF	-	68.2 ± 22.0 (30)	151.6 ± 36.0 (30)	69.0 ± 18.7 (30)
C&S	-	15.7 ± 2.8 (55)	204.1 ± 28.6 (80)	92.9 ± 17.7 (80)
R	1	4.8 ± 0.3 (6)	214.9 ± 28.4 (31)	97.8 ± 18.1 (31)
OP	25	31.6 ± 8.8	188.1 ± 29.8 (26)	85.6 ± 17.5 (26)
A	6	28.0 ± 2.1 (66)	191.7 ± 28.5 (91)	87.3 ± 17.2 (91)

[a] F, virgin peat swamp forest; LF, logged forest; FF, Fire-damaged forest; C&S, mixed croplands and shrublands; R, rice field; OP, oil palm plantation; A, *Acacia* plantation. Phytomass C losses associated with virgin peat swamp forest conversion are expressed as a difference of C stocks between the forest and the converted land and as a percentage of the stock in the forest. Values are mean ± standard error (n).

Uncontrolled fires in virgin peat swamp forest lead to large C losses from both vegetation and peat. The contribution of C loss from the peat to total C losses is the lowest when the fire occurs in virgin peat swamp forest and highest when the fire occurs in mixed croplands and shrublands, and rice fields. These C losses from fire take place in a few days and additional subsequent losses from peat decomposition are to be expected in the burnt lands. Moreover, the risk of recurrent fires is increased in burnt lands [*van der Werf et al.*, 2008]; thus further CO_2 emissions from peat combustion may also be expected.

3.2. Soil C Fluxes and Flux Changes

[25] Soil C inputs and outputs for the seven LU types are presented in Table 5. Inputs are from litterfall and root mortality; outputs are from heterotrophic respiration, CH_4 fluxes, land-clearing fires, and soluble and physical removal.

3.2.1. Soil C Inputs

[26] In virgin peat swamp forests, C inputs from fine and coarse litterfall were first calculated (4.75 ± 0.6 Mg C ha^{-1} yr^{-1}, n = 15) and later corrected in order to include large-branch fall (2.68 ± 0.4 Mg C ha^{-1} yr^{-1}, n = 33), which is common in forests. Large-branch fall amounted to 30% of total soil C inputs (from litterfall, root production and large-branch fall) as observed by *Chimner and Ewel* [2005] in a virgin peat swamp forests of Micronesia. C inputs through root mortality and litterfall in fire-damaged and logged peat swamp forests are presented in Figure 2 as a percentage of those in virgin forests.

[27] C inputs from litterfall were the highest in virgin peat swamp forests, followed by *Acacia* plantations and logged and fire-damaged forests (Table 5). Greatest C inputs through root mortality were estimated for *Acacia* and oil palm plantations compared to the other LU treatments. Total C inputs to the peat were highest in *Acacia* plantations and lowest in rice fields. In virgin, logged and fire-damaged peat swamp forests, C inputs to the peat arose mainly from the litterfall (about 80%); whereas this flux was less important in oil palm plantations (21%).

3.2.2. Soil C Outputs

3.2.2.1. Soil Respiration and C Loss From Heterotrophic Soil Respiration

[28] Mean rates of soil respiration in virgin peat swamp forests from all available studies in the literature (Table S4) ranged from 8.1 to 34.6 Mg C ha^{-1} yr^{-1} with a mean rate across all sites of 13.0 ± 2.4 Mg C ha^{-1} yr^{-1} (n = 11). Differences in soil respiration rates among virgin peat swamp forest sites were not correlated with ancillary variables such as elevation (r = −0.26; P = 0.49), rainfall (r =

Table 4. C Loss From the Peat, Vegetation, and in Total Following Uncontrolled Fires in Virgin Peat Swamp Forests (F-FF), Logged Forests (LF-FF), Mixed Croplands and Shrublands (Burnt C&S), Rice Fields (Burnt R), Oil Palm Plantations (Burnt OP), and *Acacia* Plantations (Burnt A) and Following the Conversion of Virgin Peat Swamp Forests to Oil Palm Plantations (F-OP) on Peatland[a]

LUC Type[b]	Length Time of C Loss (years)	C Loss (Mg C ha^{-1})			Contribution Peat to Total (%)
		Peat	Vegetation	Total	
F-FF	<1	284.7 ± 68.1[c]	151.6 ± 36.0	436.2 ± 77.0	65 ± 19
LF-FF	<1	284.7 ± 68.1[c]	34.6 ± 35.5	319.3 ± 76.8	89 ± 30
Burnt C&S	<1	284.7 ± 68.1[c]	15.7 ± 2.8	300.3 ± 68.2	95 ± 31
Burnt R	<1	284.7 ± 68.1[c]	4.8 ± 0.3	289.5 ± 68.1	98 ± 33
Burnt OP	<1	284.7 ± 68.1[c]	31.6 ± 8.8	316.3 ± 68.7	90 ± 29
Burnt A	<1	284.7 ± 68.1[c]	28.0 ± 2.1	312.7 ± 68.2	90 ± 29
F-OP	25	269.5 ± 86.6	157.7 ± 26.8	427.2 ± 90.7	63 ± 24

[a] The last column indicates the contribution of peat C loss to total C loss. Values are mean ± standard error.

[b] LUC, land use change.

[c] Corresponding to an average burnt peat depth of 40.0 ± 7.9 cm (n = 4) (original data in Table S2).

Table 5. Soil C Inputs, Respiration, and C Outputs for Different Land Use Treatments on Tropical Peatlands[a]

		Soil C Inputs				Soil C Outputs					
Land Use	WT	Litterfall	Roots	Total	$CO_{2\ Total}$	$CO_{2\ Hetero}$	CH_4	Fires	S&PR	Total	Balance[c]
F	−12 ± 7 (7)	7.4 ± 0.7 (24)	1.5 ± 0.8 (9)	8.9 ± 1.4 (33)	13 ± 2.4 (11)	6.9 ± 1.3 (11)	0.028 ± 0.010 (8)	-	1 ± 0.5 (1)	7.9 ± 1.4 (20)	**1.0 ± 1.7 (53)**
LF		4.6 ± 1.6 (30)	0.9 ± 0.5 (30)	5.5 ± 1.7 (30)	n.a.	n.a.	n.a.	-	1 ± 0.5 (1)	n.a.	n.a.
FF	−30 ± 7 (7)	3.9 ± 1.5 (32)	0.7 ± 0.4 (32)	4.6 ± 1.5 (32)	9.1 ± 1.6 (7)	n.a.	0.002 ± 0.000 (2)	-	1 ± 0.5 (1)	n.a.	n.a.
C&S	−43 ± 7 (18)	2.4 ± 0.6 (5)	1.9 ± 0.8 (4)	4.2 ± 1.0 (9)	17.6 ± 1.9 (21)	n.a.	0.016 ± 0.010 (9)	n.a.	1 ± 0.5 (1)	n.a.	n.a.
R	−3 ± 5 (3)	1.0 ± 0.3 (3)	1.5 ± 0.2 (3)	2.5 ± 0.3 (6)	14.2 ± 4.2 (4)	n.a.	0.155 ± 0.082 (4)	n.a.	1 ± 0.5 (1)	n.a.	n.a.
OP	−60 ± 5 (1)	1.5 ± 0.1 (4)	3.6 ± 1.1 (4)	5.0 ± 1.1 (8)	12.7 ± 2.7 (2)	9.3 ± 2.7 (5)	−0.0002 ± 0.000 (1)	4.5 ± 0.03 (14)	1 ± 0.5 (1)	14.8 ± 2.8 (21)	**−9.8 ± 3.0 (29)**
A	−90 ± 10[b]	5.1 ± 0.3 (7)	6.0 ± 0.3 (1)	11.1 ± 1.0 (8)	n.a.	n.a.	n.a.	7.1 ± 0.08 (14)	1 ± 0.5 (1)	n.a.	n.a.

[a] Soil C inputs are from litterfall and root mortality, respiration is $CO_{2\ Total}$, and C outputs are from heterotrophic respiration ($CO_{2\ Hetero}$), CH_4 fluxes, land-clearing fires, and soluble and physical removal (S&PR). Land use treatments are as follows: F, virgin peat swamp forest; LF, logged peat forest; FF, fire-damaged peat forest; C&S, croplands and shrublands; R, rice field. OP, oil palm plantation; and A, *Acacia* plantation. Values are mean ± standard error (*n*), expressed in Mg C ha^{-1} yr^{-1}. Water table (WT) depth is indicated in cm; n.a., not available.

[b] According to *Rieley and Page* [2008].

[c] The balance represents the net peat C accumulation (in the virgin peat swamp forest) and loss (in the oil palm plantation) rates.

−0.32; $P = 0.38$), air temperature ($r = 0.3$; $P = 0.39$), soil temperature ($r = 0.16$; $P = 0.84$) or depth to water table ($r = -0.14$; $P = 0.77$). Mean rates of soil CO_2 emissions in other land uses ranged from 2.6 to 35.3 Mg C ha^{1} yr^{-1} with an average rate of 15.3 ± 1.2 Mg C ha^{-1} yr^{-1} ($n = 41$). Soil CO_2 emissions from virgin peat swamp forests were not statistically different from that in other land uses ($P = 0.3883$) although soil temperatures and water table levels were significantly impacted by LUC. Among the disturbed land use categories there was only a marginal statistical difference in soil CO_2 emissions ($P = 0.0747$) and these emissions were significantly ($P = 0.0014$) and negatively correlated ($r = -0.53$) with the mean water table level. Mean soil respiration rates in the different LU treatments are presented in Table 5. No measurements in logged forest or *Acacia* plantations on peat were available.

[29] The effect size of LUC on soil CO_2 emissions ranged from −2.2 ± 0.7 (conversion of a virgin peat swamp forest to a lowland rice field) to 5.8 ± 1.9 (conversion to a coconut plantation) (Figure 3a). The effect size was significantly different from zero for ten of the nineteen LUC studies, of which five were negative (conversion to croplands and rice fields) and 5 were positive (conversion to drained and burnt forests, and croplands). In the studies where the effect size was significantly negative, the water table level (when provided by the authors) increased or remained similar after LUC. In the studies where the effect size was significantly positive, the water table level decreased after LUC, and the soil temperature increased. The combined effect size of 0.3 ± 0.4 was not significantly different from zero ($P = 0.4489$) indicating no consistent effect on soil respiration rates due to conversion of virgin peat swamp forests to other LUs.

[30] From our estimates of soil heterotrophic respiration rates (Table 5), the contribution of heterotrophic soil respiration to total soil respiration amounted to 53 ± 14 and 71 ± 26% in virgin peat swamp forests and oil palm plantations on peat, respectively. The mean root respiration rate of oil palms on peat (3.4 ± 0.4 Mg C ha^{-1} yr^{-1}, $n = 3$) is the average of root respiration rates (for maintenance and growth) of 2.7, 3.5 and 4.0 Mg C ha^{-1} yr^{-1} over a 16 year period in oil palm ecosystems planted on peatland at a density of 120, 160 and 200 palms ha^{-1}, respectively [*Henson and Dolmat*, 2003].

3.2.2.2. Soil CH_4 Emissions

[31] Mean rates of soil CH_4 emissions in virgin peat swamp forests from all available studies (Table S5) ranged from 0.2 to 72.3 kg C ha^{-1} yr^{-1}, with a mean rate across all sites of 28.5 ± 9.7 kg C ha^{1} yr^{-1} ($n = 8$). In rice fields, emissions of CH_4 amounted to an average value of 155.1 ± 82.4 kg C ha^{-1} yr^{-1} ($n = 4$). In the other LUs, mean soil CH_4 fluxes (9.9 ± 5.4 kg C ha^{1} yr^{-1}, $n = 17$) were significantly lower ($P = 0.0047$) than in virgin peat swamp forests and rice fields. Mean soil temperature was higher in the other LUs (27.1°C) than in the virgin peat swamp forest (25.7°C) and mean water table level was the highest in the rice fields (−3.3 cm), followed by the virgin peat swamp forest (−13 cm) and other LUs (−30.6 cm). Methane fluxes were positively correlated ($r = 0.54$; $P = 0.0149$) with the water table depth. The effect size of LUC on emissions of CH_4

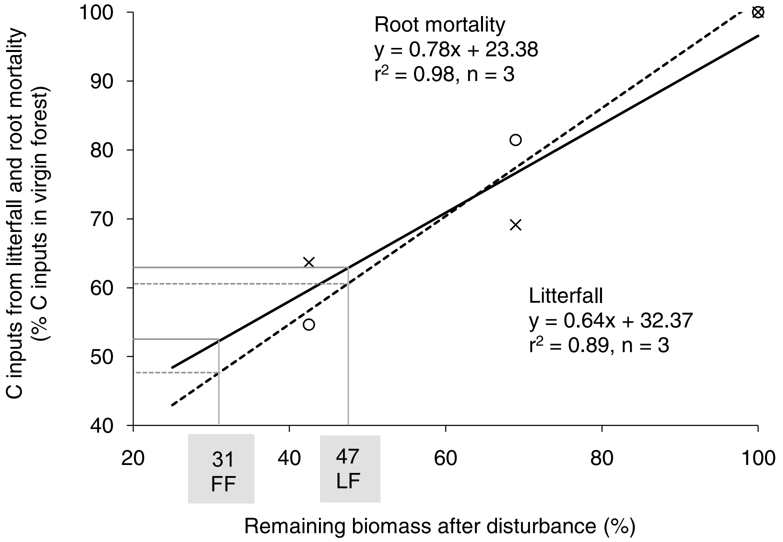

Figure 2. C inputs from litterfall (cross) and root mortality (open circle) (expressed as a percentage of C inputs in a virgin forest) as a function of the percentage of remaining biomass after disturbance. The relationships (solid and dotted line for litterfall and root mortality, respectively) obtained using data from *Hertel et al.* [2009], associated r^2, and number of observations (n) are specified. In fire-damaged peat swamp forests (FF), C inputs through root mortality and litterfall amounted to 48 ± 12% and 52 ± 19% of that in the virgin peat swamp forest, respectively. In logged peat swamp forests (LF), C inputs through root mortality and litterfall amounted to 61 ± 13% and 62 ± 21% of that in the virgin peat swamp forest, respectively.

ranged from 2.2 ± 0.7 (conversion of virgin peat swamp forest to a drained forest) to 1.2 ± 0.7 (conversion of virgin peat swamp forest to an abandoned rice field) (Figure 3b). The overall effect size was 0.4 ± 0.2 and was significantly different from zero ($P = 0.0425$) indicating a small decrease of CH_4 emissions with the conversion of virgin peat swamp forests to another LU, including rice cultivation.

3.2.2.3. Peat C Loss From Land-Clearing Fires

[32] Using the average surface peat C density of 56.7 kg C m^{-3} calculated in this study (section 3.1) and depths of peat burnt of 0.2 m and 0.1 m in oil palm and *Acacia* plantations, respectively [*Rieley and Page*, 2008], land-clearing fires would lead to peat C stock losses of 113.4 ± 0.6 and 56.7 ± 0.6 Mg C ha^{-1} in oil palm and *Acacia* plantations, respectively (expressed as C fluxes in Table 5).

3.3. Combination of the Stock and Flux Approaches for Assessing C Loss From Virgin Peat Swamp Forest Conversion

[33] In the virgin peat swamp forest, the balance between soil C inputs and outputs gives a net peat accumulation rate (Table 5), which is near the middle of the range 0.59–1.45 Mg C ha^{-1} yr^{-1} estimated by *Sorensen* [1993] and similar to the current accumulation rate of 0.94 Mg C ha^{-1} yr^{-1} measured by *Page et al.* [2004] at a site in Kalimantan. The most important C fluxes contributing to the peat C balance in the virgin peat swamp forest are the input from litterfall and the output from heterotrophic soil respiration. Among the other LU categories, sufficient data was available to calculate the balance between soil C inputs and outputs in

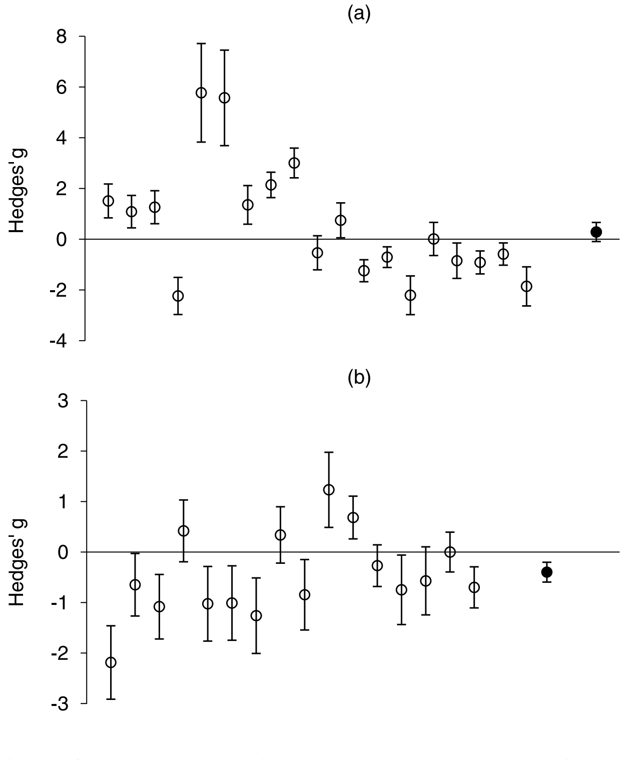

Figure 3. Mean effect size (Hedges' *g*) and standard error of individual (open circle) and overall (closed circle) land use change on soil emissions of (a) CO_2 and (b) CH_4 in tropical peatlands.

oil palm plantations only. In this LU category, C enters the peat mostly through root mortality and is lost from the peat mostly through heterotrophic soil respiration and land-clearing fires. Oxidation of CH_4 in the peat was negligible in the overall budget. The difference between the balance of peat C inputs and outputs in the virgin peat swamp forest and that in the oil palm plantation represents a net total loss from the soil of 10.8 ± 3.5 Mg C ha^{-1} yr^{-1}. Total C loss from the peat and vegetation cover change over 25 years is presented in Table 4. The rate of C loss from this conversion is then estimated at 17.1 ± 3.6 Mg C ha^{-1} yr^{1} during 25 years.

4. Discussion

4.1. Contribution of This Study to Current and Future Knowledge on C Fluxes Released From LUC in Tropical Peatlands

[34] Our results revealed that C losses from uncontrolled fires are extremely high, especially when the fire occurs in virgin peat swamp forests. These results may be useful combined with land cover change data assessed from satellite imagery for calculating CO_2 emissions from fires. For instance, *Langner et al.* [2007] estimated that in Borneo 591,816 and 120,377 ha of virgin peat swamp forests were burnt in 2002 and 2005, respectively. With our estimate of C loss from uncontrolled fires in virgin peat swamp forests, we can estimate that these fires have released 277.5 ± 48.2 and 56.4 ± 9.8 Tg C in the atmosphere in 2002 and 2005, respectively. *Ballhorn et al.* [2009] estimated that 49.1 ± 26.8 Tg C and 0.25 ± 0.14 Pg C were released from burnt peat in their study area and for the whole Indonesia, respectively, during the 2006 El Niño fires. Using their observations on land covers affected by fires (78% in logged peat forests, 16% in previously burnt peat forests, and assuming that the remaining 6% corresponded to croplands and shrublands), we can assess total C losses of 59.1 ± 27.7 Tg C and 0.31 ± 0.14 Pg C from both peat and vegetation, in their study area and for the whole Indonesia, respectively. C losses from the conversion of virgin peat swamp forests to oil palm plantations are also very high although these losses take place over a time period of 25 years. We could not calculate the peat C input-output balances in most of the LU treatments due to current gaps in knowledge regarding peat C fluxes, which we will discuss in section 4.2. Nevertheless the average peat C fluxes that we provide here may be useful for further studies measuring only one of the peat C fluxes (for instance heterotrophic soil respiration) and aiming to use the soil C input-output balance approach. Our average peat C fluxes may also be used in formulating hypothesis for future work (e.g., heterotrophic soil respiration contributes 50% to total soil respiration) and calculating an approximate peat C input-output balance for comparing it with peat C loss assessed using the C stock change approach.

4.2. Gaps on C Stocks and Fluxes in Tropical Peatlands

[35] From our review we conclude that data on C stocks and fluxes in tropical peatlands are scarce, which is a serious concern given the important role that these forests play in GHG emissions in the Southeast Asia region. For instance, so far there is no published allometric biomass equation specific to tropical virgin peat swamp forest stands, so authors generally use relationships developed from trees growing on mineral soils to estimate aboveground biomass. Destructive sampling for developing an allometric biomass equation specific to tropical virgin peat swamp forest stands would improve C stock assessments. The few available data on C stocks in virgin peat swamp forests showed a high variability among the different studies (from 9.25 ± 3.1 to 351.3 ± 84.8 Mg C ha^{-1} in the aboveground biomass; see Table S1), arising from differences in methods of estimation of C stocks but also from ecological differences between peat forest types. Our estimate of mean aboveground C stock in virgin peat swamp forest is similar to that of around 220 Mg C ha^{-1} proposed by *Fargione et al.* [2008] but higher than estimations made by *Rieley and Page* [2008] and *Uryu et al.* [2008] of about 150 Mg C ha^{1}. Our figures (Table 1) give a root:shoot ratio of 0.136 in agreement with the estimate of *van Noordwijk et al.* [2004] for tropical lowland humid forests.

[36] More investigation on the types of LUC occurring in tropical peatlands and their dynamic is still necessary. Currently, the extent of logging activity within virgin peat swamp forests in Southeast Asia is unknown and the magnitude and dynamic of fires are still not well quantified [*van der Werf et al.*, 2008]. Additionally, while there has been much attention to the increasing area of oil palm planted on peatlands, quantifying the extent of *Acacia* plantations has not received as much attention. This last LU type has been understudied compared to oil palm plantations (Table 5) and some measurements of soil GHGs emissions would be required to improve our estimates of its impact on the atmosphere. Given the high C losses from burnt peat associated with land-clearing fires or uncontrolled fires, more measurements of the depth of peat burnt with the associated C density are necessary. Finally, there has been no measurement of soluble and physical C removal in tropical peatlands. Our assessment of soil C loss in oil palm plantations on peatlands, using data from northern peatlands, demonstrated however that these losses may be significant and should be considered.

4.3. Methods for Assessing Peat C Loss From LUC

[37] One of the major concerns regarding LUC in tropical peatlands is the estimation of C loss from the peat. For this, two approaches are available: the stock difference approach and the so-called input-output approach [*IPCC*, 2006]. An accurate assessment of soil C stock changes following LUC in tropical peatlands requires C stocks measurements over the full depth of the peat profile, as achieved by *Schipper and McLeod* [2002] in New Zealand. Indeed, combined physical and chemical activities in the topsoil associated with drainage, peat subsidence and fires may complicate the identification of soil layers that should be compared before and after LUC. Therefore, studies on superficial layers of peat soils do not provide a valid approach for comparative studies of changes in peat C stocks associated with LUC. For instance, *Ywih et al.* [2009] compared soil C stocks in the top 50 cm of a virgin peat swamp forest to that in oil palm plantations on peat, aged 1, 3, 4 and 5 years old. The

authors found no significant differences in soil C stocks between treatments and concluded that "the conversion of secondary forest on peat to initial stages of oil palm plantation seems to not exert any significant difference on C storage."

[38] On the other hand, estimating C stocks in peat with any reasonable degree of precision is nearly impossible. Peats are heterogeneous, with zones of high bulk density due to the presence of logs, and zones of very low bulk density. Small errors in bulk density estimates, for example due to compaction during sample collection, lead to large errors in estimated C stocks, and these are likely because we are operating at the limits of most methods (e.g., the core method). Also, bulk density does not vary in predictable ways in tropical peats [*Page et al.*, 2004; *Kool et al.*, 2006]. Finally, accurately estimating the volume of peat in order to be able to scale bulk density estimates to an area basis is difficult because the surface is often very irregular [*Andriesse*, 1988] as is the contact with the mineral substrate [*Jaenicke et al.*, 2008].

[39] Given the problems cited above, a better approach for assessing peat C loss after LUC is offered through the input-output method. This approach requires knowledge of the main C inputs (litterfall and root mortality) and the major outputs (soil heterotrophic respiration rates and loss associated with fires). Soil respiration may be a useful indicator of peat C loss [*Wösten et al.*, 1997; *Rieley and Page*, 2008; *Uryu et al.*, 2008; *Couwenberg et al.*, 2010; *Hooijer et al.*, 2010]. However, the heterotrophic component must be estimated and outputs have to be balanced against inputs in order to evaluate how much C the peat is losing or sequestering. Then the balance between inputs and outputs before and after LUC must be compared [*IPCC*, 2006] in order to assess peat C loss associated with LUC.

[40] A second element that needs improvement is our understanding of the nature of the relationship between drainage and organic C loss. Several authors have used a linear relationship between water table depth and C loss from peat [*Uryu et al.*, 2008; *Couwenberg et al.*, 2010; *Hooijer et al.*, 2010], yet we know that soil heterotrophic respiration does not decrease linearly with increasing water content in saturated conditions [*Linn and Doran*, 1984; *Cook and Orchard*, 2008]. Thus, these relationships likely overestimate CO_2 emissions from peat decomposition. Comparing the estimates from peat decomposition in oil palm plantations proposed by *Rieley and Page* [2008] and *Uryu et al.* [2008] with our results show that the modeled estimates are 1.9 to 2.5 times higher than our estimate of soil heterotrophic respiration rate and 1.6 to 2.2 times higher than our estimate of peat C loss after LUC.

[41] Assessment of peat soil C loss from subsidence constitutes an interesting approach. Subsidence is a function of three processes in drained peats: organic matter mineralization, compaction and shrinkage. Uncertainties associated with the parameters involved, notably the contribution of mineralization to subsidence relative to the other processes, peat OM decomposition rate, relationship between drainage depth and subsidence rate, peat layers C content and bulk densities, etc. are still very high, which makes the estimates unreliable. *Kool et al.* [2006] measured subsidence rates of 40–70 cm yr^{-1} during the 6 years immediately following the collapse of a peat dome in central Kalimantan, caused by the construction of a canal for wood extraction. During this initial stage of subsidence the authors estimated that the subsidence of the peat was 99% due to consolidation [*Kool et al.*, 2006]. At another site, *Wösten et al.* [1997] estimated that oxidation contributed around 60% to peat subsidence over a 5 year period, 30 years after LUC. In this study, the peat subsidence was relatively low (~2 cm yr^{-1}) and could be attributed to shrinkage and organic matter oxidation, only. Thus, it appears that consolidation processes are more important immediately after LUC, while oxidation and shrinkage are more important in later phases after the collapse of the peat dome. More observations are necessary to resolve this if we want to be able to estimate C losses directly from subsidence.

[42] The meta-analysis indicated no consistent overall effect on soil respiration due to conversion of virgin peat swamp forests. Negative effect sizes (i.e., decreased soil respiration) observed for some LUCs were compensated in the analysis by the positive effect sizes (i.e., increased soil respiration) from other LUCs. Significant negative effect size corresponded to situations of similar or increased water table levels. Significant positive effect size corresponded to situations of decreased water table levels and increased soil temperatures. Situations where soil respiration remains similar after LUC despite a decrease in the water table level may be explained by the change in vegetation cover. Indeed root respiration may decrease following those LUCs where root density and activity decrease in the land cover replacing the virgin peat swamp forest. Then increased soil heterotrophic respiration, favored by decreased water table level may be compensated by decreased soil autotrophic respiration. This is the case for our assessment of the conversion of a virgin peat swamp forest into an oil palm plantation where total soil respiration remains similar but soil heterotrophic respiration does indeed increase (Table 5). Therefore, hydrology, soil temperature but also vegetation cover changes are critical in driving C cycle changes. The effect of nutrient additions through fertilization in tropical peats has not been systematically studied, but is likely also a factor in the assessment of overall LUC effects.

5. Conclusion

[43] The fate of tropical peat swamp forests is a major concern within the framework of climate change because of the high amount of C they currently store and could carry on storing, and the consequences of LUC for CO_2 release into the atmosphere. These ecosystems are therefore an important issue for climate change mitigation mechanisms, such as REDD (Reducing Emissions from Deforestation and forest Degradation). If the assessment on CO_2 release following LUC in tropical peatlands is overestimated, the expected climate change mitigation by the implementation of REDD will not be achieved.

[44] Our literature review and analysis have demonstrated that many gaps still remain in our understanding of the C cycle in tropical peatlands. Among the main gaps are those

related to belowground processes, particularly the heterotrophic and autotrophic components of soil respiration. Global studies on specific topics such as oil palm plantations and biofuels generally misunderstand the process of soil respiration and consider it as a direct measurement of soil C losses when, in fact, only a fraction of this flux (the heterotrophic one) is involved in peat C loss and this fraction has to be balanced with main C inputs to the soil to assess peat C loss.

[45] This review has focused on the C cycle only and has not raised the issue of nitrous oxide (N_2O) flux changes associated with LUC in tropical peatlands. Nitrous oxide has a GWP of 298 [*Forster et al.*, 2007] over a 100 year time horizon and LUC may raise emissions because (1) after drainage denitrification may switch from N_2 production to N_2O production, (2) agriculture often uses N fertilizers which are known to increase N_2O emissions, and (3) N_2O is emitted during fires. Thus, there is much yet to be done on understanding the biogeochemistry of land use change in tropical peatlands and the global attention on the importance of this ecosystem with respect to C emissions should be an impetus to the research community to redouble efforts in these ecosystems.

[46] Finally, our study focused on LUC in Southeast Asian peatlands although Amazonian peatlands may also be of global significance in terms of both area and future potential high deforestation [*Lähteenoja et al.*, 2009]. Biogeochemical work in these peatlands are required to verify that generalizations form Southeast Asia have global application.

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